The Effects of Volcanic Ash on

Development, Reproduction, and Mortality

Of the Western Spruce Budworm.

Intra-campus MEMORANDUM

UNIVERSITY OF MONTANA

DATE: March 24, 1981

TO: David Fellin

FROM: Jerry J. Bromenshenk

RE: Cooperative Agreement #INT-80-105-CA

Attached is the status report, due March 31, 1981, concerning our cooperative study of "The Effects of Volcanic Ash on the Development, Reproduction, and Mortality of the Western Spruce Budworm"

It is my understanding from our conversation that you will transmit this report to the Station Director, Intermountain Forest and Range Experiment Station, 507 25th Street, Ogden, Utah.

If you have any comments or questions, please contact me. I shall be in Corvallis, OR March 29, 30, and 31. I shall be in my office throughout this week and shall be back by April 1. As I mentioned, I intend to meet with Lucille Clark and Milt Steltzker while in Corvallis and will carry back the ingredients needed for the synthetic diet for the spruce budworm larvae.

THE EFFECTS OF VOLCANIC ASH ON THE DEVELOPMENT, REPRODUCTION, AND MORTALITY OF THE WESTERN SPRUCE BUDWORM

Cooperative Agreement #INT-80-105-CA

Status Report
March 24, 1981

by

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Introduction

We received authorization to proceed with this project on September 8, 1980. Most of the work performed since that time has been preparatory--aimed at initiating the major research effort by April 1, 1981.

Ash Properties

In October, 1980, we obtained approximately 150 pounds of volcanic ash from St. Maries, Idaho, and Ritzville, Washington. These towns were in the path of the heaviest ash fallout from the May 18 eruption. The ash from these sites is relatively fine sized and more typical of the ash that fell on eastern Washington, northern Idaho, and western Montana, than ash that fell nearer to Mt. St. Helens. (Maps of the distribution, weight, and thickness of ash deposits are presented in the papers by Cook et al., 1981, and Johansen, 1980, which are included in Appendix A of this report.)

In addition to ash, we also obtained specimens of Douglas fir, ponderosa pine, and juniper foliage which still retained ash from the earlier eruptions. The Douglas fir and ponderosa pine samples were washed with distilled water, the wash water was then filtered using 0.45 µm millipore discs, and weight of ash on foliage and on foliage and stems was computed on a dry weight basis (oven-dried). D. Bilderback, Department of Botany, performed similar tests on a larger number of samples for another Forest Service Cooperative study. He obtained foliage from sites in the same areas. Data from both studies is presented in Tables 1 and 2. Bilderback's data displays higher levels of ash on Douglas fir; both experiments show more ash on fir than on pine foliage. Bilderback also examined the ash on the foliage via scanning E.M. and found a proliferation of fungus on the needles of fir that appeared to be anchoring the dust--in fact he was unable to wash more than approximately 80% of the ash off. Our samples were stored until January and appeared to have lost some ash in the collection bags which probably accounts for the lower recovery figures. The purpose for including this data is to provide estimates of the

Table 1

Ash/Foliage Ratios
Supplied by the Environmental Studies Laboratory

Douglas Fir

Sample No.	Grams Ash/ Grams Needle	Grams Ash/ Grams Needle and Stem
1a	0.27	--
1b	0.18	0.12
2a	0.14	0.09
2b	0.13	0.09
3a	0.27	0.20
3b	0.16	0.10
Average	0.19	0.12

Ponderosa Pine

Year of Growth	Ash Weight	Needle and Stem Weight	Grams Ash/ Grams Needle and Stem
1980	.0399	44.76	.00089
1979	.1417	50.00	2.83×10^{-3}
1978	.14086	54.04	2.61×10^{-3}
1977	.0426	23.54	1.81×10^{-3}

Table 2

Ash/Foliage Ratios
Supplied by D. Bilderback

Sample No.	Grams Ash/ Grams Needle
0	0
1	0
2	0.003
5	0.0054
7	0.094
8	0.543
9	0.361
10	0.441
11	0.405
13	0.382
15	0.434
16	0.085
17	0.10
18	0.084
19	0.044
20	0.077
22	0.009
23	0.004
24	0.017

amount of ash that may remain on foliage after weathering for several months. Obviously, the maximum amount of ash retained for short periods is limited by the quantity of ash that can be piled onto the needles before it begins to cascade off. Wet foliage appears to hold more ash in a cement-like coating. Dry foliage rapidly sheds ash under windy conditions.

Chemically, the ash is 60%-70% SiO_2 by weight (Hooper et al., 1980; Fruchter et al., 1980) at sites farther than 140 miles from the volcano (note Richland, Washington, data in Table 3). Table 3 lists the results of a cooperative effort carried out shortly after the May 18 eruption. In addition to the chemical components listed, a similar summary in Cook et al. (1981) noted that depending on where the ash fell, it included: Cd, <3 to 4 ppm; As, <2 to 4 ppm; Cr, <10 to 30 ppm; Pb, <5 to 13 ppm; Hg, <10 ppb; Ni, <6 to 27 ppm; Cu, <25 to 40 ppm; Zn, <45 to 70 ppm; Se, <1 ppm; and Co, <15 to 30 ppm. Thus, the ash does contain toxic chemicals such as arsenic, lead, mercury, fluoride, and cadmium, although in relatively low concentrations. Physically, the ash contains jagged or glass-like shreds or particles that are exceedingly abrasive, as evidenced by scratched finishes of vehicles where the ash was brushed off rather than washed off. One truck that arrived in Missoula after traveling through the ash fall in northern Idaho looked like it had been sand-blasted in preparation for re-painting. The edges of paint around any nicks and chips on the front ofthe vehicle were feathered and the metal was polished.

Effects of Ash on Insects

Donald Scott conducted a literature review and computer search of reports on the effects of volcanic ash on insects (Washington State University's Conference on the Aftermath of Mt. St. Helens, July 8-9, 1980). He found that effects primarily are: (1) an immediate toxic effect attributed to abrasion of and absorption through the waxy layer of the epicuticle which leads to dessication, and (2) indirect longer-term effects of differential species death and recolonization of affected regions.

At this same conference, Roger Akre reported that insects were affected more by the ash than other organisms, mainly because of their small size and susceptibility to dessication. Many were buried, trapped, and could neither crawl nor fly out of it. Ash abraded the waxy layer of the cuticle, leading to rapid water loss. House flies dusted with ash in 8 hours lost nearly 40% of their body moisture (based on weight) and died within 24 hours. Similar results were seen with cockroaches. Grain beetles were more resistant to dessication, losing less than 3% of their weight in 8 hours and all were alive after 24 hours. Insects such as many species of flies, solitary wasps, leaf-rollers, aphids, and some beetles survived the ash fall, presumably because the insects were in immature stages of their life cycles and/or protected locations. However, recently-hatched grasshoppers were eradicated.

Johansen (1980) reported severe losses of honey bees, yellowjackets, and bumblebees. Beneficial insects such as honey and other pollinator bees were hard hit, as were predatory and parasitic wasps and yellowjackets (Hymenoptera). These insects were virtually eliminated from many areas in Washington. Studies have been initiated to document recolonization of these areas. Johansen postulated that the ash not only scurfed the surface wax layer but also clogged

Table 3

Mt. St. Helens Volcanic Ash Composition Collected in Richland, Washington; Helena, Bozeman, and Missoula, Montana*

Element, Compound or Physical Parameter Measured		Battelle Pacific Northwest, Richland, Washington; Airplane Collection; Neutron Activation[1] Total	H₂O Sol. 10:1	Montana State Univ. (USDA), Bozeman; Atomic Absorption bulk collection from surfaces of materials	Montana State Air Quality Bureau, Helena; Atomic Absorption [2]Bulk Coll.	/Hi vol Filter[3]	Environmental Studies Lab, Missoula, Montana Sulfur--Leco Induction Fluoride--Ion Specific Bulk Collections
Aluminum	Al	9.9 %	2.2 ppm	8.6% as Al_2O_3	--	--	--
Calcium	Ca	3.9 %	32 ppm	--	--	--	--
Iron	Fe	3.9 %	1.76 ppm	4.7% as Fe_2O_3	1000 ppm[4]	--	--
Titanium	Ti	0.41%	--	--	--	--	--
Magnesium	Mg	1.67%	2.6 ppm	<52 ppm	--	--	--
Potassium	K	1.3 %	5.9 ppm	--	--	--	--
Silicon	Si	28.0 %	1.2 ppm	80.4% as SiO_2	--	--	--
Arsenic	As	--	--	--	<1 ppm	--	--
Boron	B	34 ppm	0.025 ppm	<10 ppm	--	--	--
Copper	Cu	41 ppm	0.017 ppm	26 ppm	<10 ppm	<0.010 $\mu g/m^3$	--
Cobalt	Co	19 ppm	--	--	--	--	--
Cadmium	Cd	--	<0.01 ppm	--	<5 ppm	<1 $\mu g/m^3$	--
Chromium	Cr	31 ppm	< .005 ppm	--	<50 ppm	<13 $\mu g/m^3$	--
Lead	Pb	28 ppm	0.014 ppm	--	<50 ppm	<10 $\mu g/m^3$	--
Manganese	Mn	675 ppm	0.53 ppm	--	--	--	--
Molybdenum	Mo	--	<0.01 ppm	75 ppm	--	--	--
Mercury	Hg	0.015 ppm	--	--	--	--	--
Nickle	Ni	27 ppm	0.021 ppm	--	--	--	--
Sodium	Na	--	18.0 ppm	--	--	--	--
Selenium	Se	--		<1.3 ppm	<2 ppm	--	--
Vanadium	V	127 ppm	<.02 ppm	--	--	--	--
Zinc	Zn	100 ppm	0.044 ppm	16 ppm	10 ppm	--	--
Lithium	Li	--	15 ppb	--	--	--	--
Sulfur	S	--	--	--	--	--	850-1000 ppm
Sulfate	SO_4	--	--	--	1900 ppm	--	--
Nitrate	NO_3/NO_2	--	--	--	30 ppm	--	--
pH		--	--	--	--	--	6.5 pH
Radioactivity		--	--	--	nothing detected above background[5]		--
Fluoride	F	--	--	--	--	--	10 ppm H_2O soluble/48 ppm total
Micro. Char.		--	--	--	glass like shreds	--	--

*Richland, Washington, 140 air miles from Mt. St. Helens; Bozeman, 530 air miles; Helena, 470 air miles; Missoula, 410 air miles.
[1]Battelle also found some NO_3^- and $SO_4^=$ in ash by activation analysis; [2]H_2O leachables; [3]acid leachables; [4]water soluble fraction was analyzed for soluble (ferrous) iron and only a trace was found; [5]measured with a geyger counter

the tracheal (breathing) tubes, since many of the particles are less than 1 μm in diameter. Thus far, his studies have not confirmed the latter, although he believes many insects buried under the dust died of suffocation (personal communication, 1981).

Many of the studies discussed at the Washington State University Conference, the report by Cook et al. (1981), and my conversations with entomologists in Idaho, Washington, and Oregon are ongoing, and most results are of a very preliminary nature. Abrasion of the waxy layer of the integument and subsequent dessication has only been shown to be a likely cause of death in a few cases. The ash does abrade the lining of the intestine and as such may affect insects feeding on ash-coated foliage. A few experiments have been carried out using larvae of insects that feed on broad-leaved plants. There were little or no discernible effects. However, none of these studies were of long duration nor of any substantial size--most were quick tests.

It is our impression that the mechanisms underlying the observed effects of ash on insects are still very poorly understood, and most of the data currently available is based on a limited base and is subjected to interpretation founded on first impressions rather than rigorous studies. Thus, there was a rapid proliferation of publications rushed to press within days or weeks of the first major eruption. At this time, the serious research efforts are ongoing, and data from these will not be ready for review until the end of this next field season. Hopefully, future publications will reflect a concerted effort to verify the hypotheses thrown out by the early publications and a willingness to reject these if they are incorrect.

In designing the Spruce Budworm study, we have approached the problem from the perspective that little is known about possible effects, and as such the work plan must remain somewhat flexible in order that appropriate modifications can be made based on statistical and other evaluations of the emergent data. Thus, if the feeding toxicity tests indicate that sample size should be increased or more replicates added in order to obtain usable data, we shall incorporate these changes as needed.

Facilities, Equipment, Supplies

We indicated in our budget that we intended to retrofit the Missoula City-County Greenhouse in order to obtain the space needed for this study. This greenhouse is a relatively new facility that has been used by the University of Montana, the Missoula Weed Control District, and at times Forestry. Unfortunately, the greenhouse was poorly designed and had a tendency to overheat. We have been carrying out the modifications needed to alleviate this problem and have managed to rectify most if not all of the difficulties. We may continue to make improvements, but at present the greenhouse is usable. Tables have been set up for rearing budworm. The duct work and fan assembly has been placed in the top of the greenhouse to draw off trapped, hot air. The swamp cooler supplied by the Forest Service has been obtained, is in working condition, and is currently being installed. The Forest Service has provided cartons for holding the bolts from trees from which the budworm emerge, and these are at the greenhouse and are being used for preliminary emergence tests. J. Dewey, USFS, FPM has loaned us 1,037 plastic Randal cages

and the metal trays and supports that go along with them. These have been set up at the greenhouse. Dave Fellin supplied a hygro-thermograph to monitor humidity and temperature in the greenhouse throughout the study. It was installed this week and will be returned at the end of the experimental work.

For the feeding tests, we decided, in consultation with Forest Service personnel, that the ash could be administered to the budworm diet in one of three ways: (1) mixing of the ash with synthetic diet; (2) dusting of ash on synthetic diet; and (3) dusting of foliage. We shall discuss the first two under the section entitled Diet. The third method was attractive since it most closely simulated real world conditions but presented a technical problem of how to apply dust in a uniform, repeatable manner. We believe that we have solved this problem. We intend to utilize a modification of the procedure developed by Atkins et al. (1954) and improved by Atkins et al. (1975). Basically, this procedure consists of placing the sample to be dusted in a bell jar which is then evacuated to 18 to 22 inches of mercury. A watch glass containing a measured amount of dust (ash) is suspended in the top of the apparatus before applying the vacuum. Once the air has been exhausted from the chamber, a electrically-controlled solenoid valve is opened--the outside air imploding into the jar and uniformly dispersing the dust. Our tests indicate that foliage is more or less uniformly coated on all sides, with just slightly more on the upper surfaces. This is consistent with observations of the dust on foliage obtained in the field. Because of the fine particle size and tendency to swirl and re-entrain, the ash does coat the underside of needles almost as heavily as the upper surfaces.

Our version of this duster contains two dusting units (jars) in a 4x4x2 foot plywood box with clear plexiglass panels set into the front as doors. All controls are mounted on the outside of the cabinet. The box and doors are intended to provide protection to the operators in case one of the dusters implodes. Each of the two dusters is large enough to coat 12 branchlets (sized to fit into a Randal cage) simultaneously. The duster assembly has been completed and is currently being tested in order to ascertain application rates, i.e., how much ash is needed to produce a specified amount of ash over a unit of surface area and/or a particular weight of ash on needles on a gram ash/gram needle dry weight basis.

At present, we have purchased and collected together all of the major supplies needed for the larval tests. At a later date, we will obtain the adult rearing cages from the Forest Service. Two of our major needs were: (1) an adequate source of budworm larvae, and (2) a supplier of the ingredients or of the made up synthetic diet. We have resolved both of these.

Budworm Population

In February, Leon Theroux collected bolts from a site at Lubrecht Forest. The emergence results are given in Table 4. It should be readily evident that the number of emergent larvae was very low.

In early March, Leon Theroux (Forest Service) and Robert Postle (Environmental Studies Laboratory, UM) collected 100 bolts from seven trees near Pipestone, Montana, an area that the Insect and Disease Laboratory indicated had a

Table 4

Number of Emergent Spruce Budworm Larvae from Lubrecht Forest Trees

Tree #1--Western Larch

Bolt	Date (1981)											
No.	3/1	3/2	3/3	3/4	3/6	3/7	3/8	3/9	3/10	3/11	3/12	3/15
1		1		1	1	1				1		
2					2	1	1	1	1	1		1
3		1	1			1	1					
4		1	1		3	1						
5		1	1	2	1				1		1	
6	4	4	3	3	4	3	1	2	4	1	5	
7	1	2	4	1	7	3	2	3	5	3	4	1
8	3	2		3	10	6	9	3			2	1
9			3	1	13	5	4	3	4	4	2	5
Total	8	12	13	11	41	22	18	12	15	10	14	8

Tree #2--Western Larch

Bolt	Date (1981)												
No.	2/27	3/1	3/2	3/3	3/4	3/6	3/7	3/8	3/9	3/10	3/11	3/13	3/15
1				1		2							
2													
3				1	1							2	
4		1							1				1
5	1	2		4	6	16	5	7	2	2	1	2	1
6	1		1	1	1		1	2	1			1	1
7			1			2	3	2	4	4		2	
8				4	3	4			1		1		
Total	2	3	2	11	11	24	9	11	9	7	2	7	3

Tree #3--Douglas Fir

Bolt	Date (1981)											
No.	3/1	3/2	3/3	3/4	3/6	3/7	3/8	3/9	3/10	3/11	3/13	3/15
1		1	1			1					1	
2	1	3	1	2	1	2	1					
3		1	1	1				1	1			
4					2	1	1				1	
5	1				1	1		4	2	1		
6					3	1	1		2			
7	1	1	2	1	6		1	1	2		1	
Total	3	6	5	4	13	6	4	6	7	1	3	0

Rearing started at 1:00 p.m. on 2/18/81.
Bolt numbers 1-4 were gathered from the base of the tree; bolt numbers 5-9 were gathered from the upper portion of the tree.

large budworm population in the fall of 1980. Currently, one bolt per tree is being forced in the greenhouse in order to ascertain the number of budworm that can be obtained for use. We have begun to get large numbers of larvae; after a few days lag, we began to get over 100 per day. The other 93 bolts have been stored in a walk-in cooler so that we can pull bolts whenever we need budworm larvae and delay their development so that we will have a ready supply of second instar larvae even after the larvae have passed that stage in the field.

Diet

Jacqueline Robertson, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, has supplied us with 5 pounds of diet in order to begin rearing of early stage larvae. She advocated conducting the feeding toxicity tests using 4th, 5th, or 6th instar larvae on foliage. Based on her most recent work, budworm exposed to insecticides in this manner provided data that was more precise and which was different from the responses seen with budworm exposed to insecticides while on the diet. She also indicated a growing dissatisfaction with the synthetic diet and stated she would rear on foliage alone if it were readily available. She did not have any good suggestions on how to handle the technical problems associated with attempting to rear 2nd and 3rd instar larvae on foliage, e.g., rejection of food, escape from cages. In fact, she continues to rear the early stages on diet. She was unable to provide us with any large quantity of diet due to budget restrictions. She did try to mix ash with the diet and reported that she could not see any way in which this could be accomplished in an accurate manner. Thus, she advised against administering the ash via this method.

Lucille Clark and Milt Steltzger at Corvallis, Oregon, have agreed to supply us the raw materials needed to make the diet, and I shall carry these back when I return from a business trip to Corvallis on March 31, 1981. We will obtain 42 pounds of diet, which should enable us to rear 5,000 larvae to the 4th instar. In addition, we intend to try mixing the ash into the diet and, if successful, will use this in our testing of the responses of the early larval stages. Our other option for administering the ash to feeding 2nd and 3rd instar larvae is by dusting the diet media after it is poured and has solidified. Rather than pour large blocks which then must be cut-up and dusted, we may pour the diet media directly into petri dishes, covering the bottom of each dish with a thin layer. Using a scalpel, slits will be cut into the surface and each dish then coated with ash using the vacuum duster. Dave Fellin reports that this method seems to be well-suited for rearing early stage larvae, makes it easier to see the insects, seems to be accepted by them, and is less wasteful of the diet.

It is our intent to conduct ash/diet feeding tests on early stage larvae and to mass rear budworm on diet for testing with dusted foliage during the later development stages. The foliage tests will receive priority, not only for the reasons mentioned but also because conditions are more like those in nature and as such facilitate data interpretation and "real world" inferences.

Statistical Considerations

We have been working with Gayle Yamasaki, Forest Service, in designing a statistically sound and defensible experimental design. We have been reviewing the most recent toxicity testing of J. Robertson and M. Haverty, Pacific Southwest Forest and Range Experiment Station, Berkeley, California, in order to better understand sample size requirements and data treatment aspects of this sort of testing. Jackie has provided us with raw data from her controls and diesel oil (low toxicity) tests. We had hoped to be able to generate estimates of minimum number of insects required per test and the number of replicates needed for each dosage or concentration. Based on the information available to date about the effects of Mt. St. Helens ash, we have hypothesized that the ash will be of relatively low toxicity compared to modern insecticides, which is why we were looking at the control and diesel fuel treatments. Unfortunately, the Berkeley data did not provide enough values to make any meaningful tests.

In our discussions with Gayle and other Forest Service personnel, we have decided to follow the general procedure used by Robertson and Haverty. We will conduct preliminary tests, record data, then evaluate the data with respect to sample size and replications, and modify the procedure as appropriate. We will direct our efforts at obtaining dose-response curves. For example, for the feeding tests on foliage, we have set a limit for the range of ash concentrations ranging from no ash to the "holding" capacity of the dusted needles. Gayle recommends an initial attempt dividing this range into as many dose concentrations as we can handle with our staff (two full-time technicians with assistance from work-study, hourly-paid employees). He suggests a minimum of 8 dose concentrations equally divided across the range for the initial effort.

For each dosage selected, the full experiment will utilize at least 3 replications. For each replication, 20 insects/dosage will be treated--20 insects per petri dish or 10 per Randal cage. Upon completion of the tests, the data will be evaluated in order to determine if additional replications are needed and to identify, if possible, that part of the dose-response curve where effects occur. If we find changes occurring, we will then adjust the treatments to more closely observe the critical area of the dose-response curve. We will also be examining the data for any significant differences between experiments carried out at different times (e.g., experiments replicated on different days), as well as between different levels of ash.

To the degree possible, all insects tested will utilize similar age and size for each series of runs. Observation intervals will depend on the tests being performed. We will be looking at both short-term and long-term effects. Acute effects will be examined by hourly counts (e.g., 24, 48, 96, 120 hours). Chronic effects will be examined over longer periods (e.g., 7-day intervals). We anticipate that for those dosage levels at which acute responses are not observed, we shall be able to continue our observations through pupation and the pupal-adult molt or until mortality is evident in larvae or pupae. This eliminates the need for conducting separate dosing for acute versus chronic testing. Similarly, testing concerning the effects of ingestion of ash by larvae on budworm development and reproduction (e.g., rate of development, number surviving at each larval stage, as pupae and as adults, as well as egg laying and viability) is relatively easy to perform by merely continuing to observe those treatments where acute toxicity did not occur.

Gayle recommended expressing results on a percent mortality basis rather than as the raw direct counts. The results will be used to construct dosage-response lines according to the procedures utilized by Robertson and Rappaport (1979).

The major point to be made is that since the effects of volcanic ash on budworm are unknown, the experimental design will have to be adjusted based on the results of the initial testing. As soon as we have these in hand, Gayle will help us produce a more detailed approach and to make necessary changes in the general approach adapted from Robertson and Haverty.

Materials and Methods

As mentioned, we will initially follow the procedures of Robertson and Haverty. A randomized complete-block design will be used, with all treatment combinations replicated over different days or weeks (blocks). Trees from which the budowrm are obtained for testing will be randomized, as will the order in which treatments are applied and the foliage utilized for food.

Dosage delivered will be computed directly if ash is mixed into the diet (grams ash/grams diet--dry weight). For foliage, the amount applied will either be measured as the amount falling on a specified surface area (e.g., grams per unit area of a standard target such as a filter disc) and/or amount applied to each branchlet (determined by randomly selected 2 of 12 dusted branchlets for each run and determining weight before and immediately after dusting). A similar procedure will be utilized if diet is dusted.

Schedule

Currently, we have both full-time technicians working on this project as of March 23. Principal investigators from the University and the Forest Service have been meeting regularly since early January in order to design the study and locate and obtain budworm, equipment, etc. We have had a work-study student working on aspects such as the washing experiments since January. It is our intent to start the experimental work in the first week of April. Currently, we are finishing equipment construction and testing, especially the testing and calibration of the dusting apparatus. We are also evaluating the abundance of budworm on the bolts sampled in order to be sure that we have sufficient numbers of insects for this project. Although the total number of insects dosed will depend on a number of factors, the major constraint will be how many insects we can maintain and handle over the next few months. We intend to complete the experimental work by the end of August or early September which is determined primarily by the normal life cycle of the budworm and by the school session, since the new academic year begins at that time and our technicians intend to attend the fall session. We would prefer not to have a staff turnover near the end of the experiment. Final data processing will take place during the fall quarter.

Our preliminary tests should soon indicate the maximum number of tests that we will be able to carry out. As far as equipment, diet, and facilities are concerned, we currently are set up to handle as many as 5,000 budworm.

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APPENDIX A

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Impact on Agriculture of the Mount St. Helens Eruptions

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The massive volcanic eruption on 18 May 1980 of Mount St. Helens in the southwestern corner of Washington State destroyed life and property to the north, west, and east as far away as 20 to 25 kilometers. In addition, an estimated ...o 2.0 cubic kilometers of ash fell on

Summary. Ash from Mount St. Helens has fallen over a diverse agricultural area, with deposits of up to 30 kilograms per square meter. Crop losses in eastern Washington are estimated at about $100 million in 1980—about 7 percent of the normal crop value in the affected area and less than was expected initially. Production of wheat, potatoes, and apples will be normal or above normal because the favorable conditions for growth of these crops since the ashfall helped offset the losses. Alfalfa hay was severely lodged under the weight of the ash, but ash-contaminated hay is apparently nontoxic when eaten by livestock. The ash as an abrasive is lethal to certain insects, such as bees and grasshoppers, but populations are recovering. The ash has increased crop production costs by necessitating machinery repairs and increased tillage. On soil, the ash reduces water infiltration, increases surface albedo, and may continue to affect water runoff, erosion, evaporation, and soil temperature even when tilled into the soil. Ash on plant leaves reduced photosynthesis by up to 90 percent. Most plants have tended to shed the ash. With the possible exception of sulfur, the elements in the ash are either unavailable or present in very low concentrations; and no significant contribution to the nutrient status of soils is expected.

farm, range, and forest land reaching almost to the Dakotas on the east and into Canada on the north (*1*). Montana and a small part of Canada received only a light dusting, but agricultural areas in east-central Washington and adjacent northern Idaho received the ash in amounts up to 300 metric tons per hectare (Fig. 1A). An estimated 49 percent of Washington State received visible ash and 29 percent of the state received deposits of 3 millimeters or more (*2*). The heaviest deposits in Washington formed a layer 5 to 8 centimeters deep on the soil (Fig. 1C), with isolated cropland areas reporting uncompacted ash up to 15 centimeters deep. Rain beginning a few days later compacted the ash to about one-third the initial depth.

The affected area in eastern Washington consists mainly of eight counties (Fig. 1B), which, in 1979, accounted for $1.4 billion of crops and $270 million of livestock and livestock products. These values were 65 and 38 percent, respectively, of the total state crop and livestock production. The major crops include tree fruits (32,000 ha), hay (153,000 ha), potatoes (24,000 ha), cereal grains (964,000 ha), and dry edible legumes (100,000 ha). Minor ones include mint, hops, vegetable seed, and other specialty crops. The region includes a major portion of the irrigated Columbia Basin, a large dryland wheat-fallow area, and a dryland area that is cropped annually (Fig. 1).

Ash from the eruptions of 25 May and 12 June fell in southwest Washington and northwest Oregon, including farmland in the Willamette Valley, but rarely produced an uncompacted layer more than 1 cm thick. The ash from the 22 July eruption drifted northeast along the eastern edge of the Cascade range, producing a layer of ash up to 3 mm deep in northeastern Washington and light dusting into Canada.

Volcanic activity has been considerable in the northwest United States and the provinces of adjacent Canada during the past several thousand years, and the material discharged is believed to have been blown easterly about 80 percent of the time (*3*). Compared with the cumulative deposits of loess and ash to date, the soil material provided by the recent eruptions of Mount St. Helens is almost insignificant. On the other hand, these are the first volcanic eruptions to occur in the area since agriculture of any consequence began there and are probably the most massive volcanic eruptions to directly affect a temperate region of wide-scale and intensive agriculture.

The full impact of the eruptions on the soils and on the plant and animal life where ash fell will never be known and even now is mostly speculation. Initial estimates that losses to crops and livestock would be large have been revised

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downward. Potatoes and winter wheat, two of the leading cash crops in eastern Washington, have shown relatively little adverse response to the ash. Nevertheless, the ash has affected plant and animal life in various ways and is now a permanent addition to the land.

In this article, we attempt to describe how the eruptions of Mount St. Helens to date have affected or may affect soil and life in relation to agriculture. For the most part, we have limited our treatment to examples of effects or expected effects. We have also limited it to direct agricultural concerns and do not address other important issues such as the possible impact on forestry, rural society, wildlife and fisheries, or climate.

Physical and Chemical Nature of the Ash

The eruption that occurred at about 0830 Pacific Daylight Time on 18 May was mainly of pulverized dacitic and andesitic rock and volcanic glass. The resulting ash cloud caused total darkness at Pullman (390 km away) from about 1500 hours until the morning of 19 May. Most of the ash fell over a period of nearly 12 hours at Pullman and had the consistency of dry Portland cement. Significant amounts of particulates 1.0 micrometer or smaller in size were still airborne 1 week later. The ash from the eruption of 25 May was accompanied by rain and fell as a slurry.

Table 1. Textural composition of volcanic ash deposited on 18 May from the eruption of Mount St. Helens (*31*).

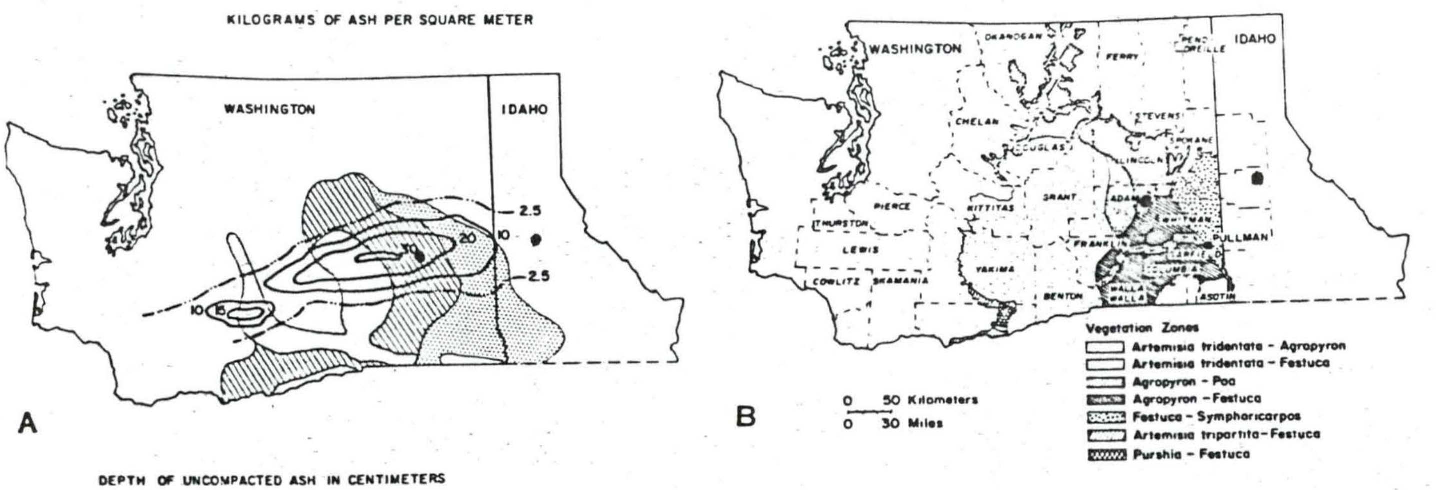
City	Distance from volcano (km)	Composition (percent by weight) Sand (> 20 μm)	Silt (2 to 20 μm)	Clay (<2 μm)	Approximate textural class
Yakima	140	85.5	9.8	4.4	Loamy sand
Richland	225	68.6	23.0	8.4	Sandy loam
Pullman	390	22.4	74.6	3.0	Silt loam

Ash accumulated on 18 May in two distinct layers. The first ash to fall (lower layer) was a medium gray color; the subsequent ash was pale gray, almost white (*4*). The lower layer made up only 20 to 40 percent of the ash in the Pullman area and is believed to have contained volcanic rock from the old cone wall or vent; the paler ash is believed to have been mainly new magma (*4*). The paler ash contained pumiceous volcanic glass and crystalline fragments of plagioclase feldspar (intermediate plagioclase, probably andesine, a Ca-Na-Al silicate material); the darker ash contained the same materials but also some Ti-rich magnetite, basaltic hornblende, and orthopyroxene (*4*).

The National Center for Disease Control (*5*) reported that some of the ash contains up to 6 percent free silica (mainly cristobalite and free quartz). Other analyses (*6, 7*) suggest less than 1 to 3 percent cristobalite or free quartz. Free silica, but not the silicates like plagioclase, can cause silicosis in humans and animals. Even if there were 5 to 10 percent free silica, the expected health hazard to people or animals is extremely small; exposure to high dust concentrations over a period of years would be necessary before serious effects would be expected to occur.

Physically, the ash consisted of jagged crystals or particles measuring 0.1 to 500 μm in size (*6*), but mostly between 1 and 100 μm. In general, the texture of the ash was progressively finer as distance from the volcano increased (Table 1).

Chemically, the ash is 60 to 70 percent SiO_2 by weight (*4, 6*), with slightly more



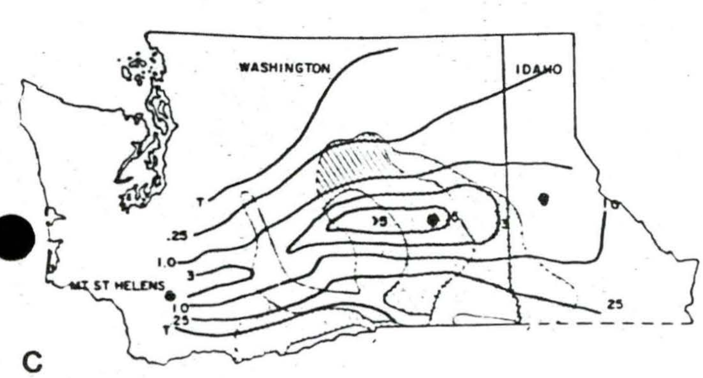


Fig. 1. (A) Weight and (C) thickness of volcanic ash deposits in eastern Washington and northern Idaho following the eruption of Mount St. Helens on 18 May (*32*). Cropping systems affected by the ashfall include an intensive cropped irrigation area in the Columbia Basin (shading), a dryland wheat-fallow area (hatching), and a dryland area cropped annually to small grains and dry peas and lentils (stippling). (B) Steppe zones of native vegetation and counties affected (*32*).

SiO_2 in the pale than in the dark ash (3). The other major components are Al_2O_3 (16 to 18 percent) and oxides of Fe, Mn, Ca, Mg, K, Na, and P (4, 6). Depending on the place where it fell, the ash also included Cd, < 3 to 4 ppm; As, < 2 to 4 ppm; Cr, 10 to 30 ppm; Co, 15 to 30 ppm; Pd, 5 to 13 ppm; Hg, < 10 ppb; Ni, 6 to 27 ppm; Cu, 25 to 40 ppm; Zn, 45 to 70 ppm; and Se, < 1 ppm (6) (ppm, parts per million; ppb, parts per billion). The ash contained 250 to 450 ppm sulfate S and had a saturated paste *p*H of 5.3, but this varied with sample (8). It also contained various chloride salts clinging to the particles; the electrical conductivity of a saturation water extract of a sample from near Pullman was 6.5 millimhos (8).

Effects of the Ash as an Abrasive

The initial effects of the ash resulted from the particulates themselves, which are highly abrasive and easily airborne. The dust is a recurring problem in agricultural areas on windy days or when it is disturbed by livestock or machinery. The Pacific Northwest is a winter precipitation region; less than 10 cm of precipitation is expected at Pullman during June through September (< 5 cm at Lind, Adams County, where deposits were heaviest). Fortunately, rainfall was 20 to 25 percent above normal in the main ashfall area during June 1980, which greatly alleviated the dust problem in the region.

The ash particles were especially destructive to insects, largely due to abrasion to the epicuticular wax layer, which caused rapid desiccation and death (9). This wax layer within the integument of the insect is only 0.25 μm thick on the average and is the principal means of protecting the insect against desiccation (9). The problem is compounded by the insects' large surface area relative to their size. Adult house flies (*Musca domestica*), brown-banded cockroach nymphs (*Supella longipalpa*), and adult orchard mason bees (*Osmia lignaria*) lost 28 to 66 percent of their body moisture and 50 to 100 percent died within 4 to 8 hours after exposure to ash at 24.5°C and 31 percent relative humidity (9). In contrast, great wax moth larvae (*Galleria mellonella*) and mealworm larvae (*Tenebris molitor*) were only slightly affected by exposure to the ash (9). Yellowjackets exposed to the ash on 18 May, when brought to the laboratory and given access to water, still died within 3 to 6 hours (10). The ash on insect bodies also affected their ability to fly and is a continuing problem for their survival in the area.

Some of the insects killed by the ash were crop pests, including the Colorado potato beetle (*Leptinotarsa decemlineata*) and grasshoppers (*Melanoplus* spp.). Adult Colorado potato beetles did not recover after 24 hours of exposure to the ash, whereas nearly 100 percent of the population survived in plots of potatoes near Yakima that were watered by overhead irrigation within 24 hours of the ashfall (11). Compared to adults, first-, second-, and third-instar Colorado potato beetles were more sensitive and fourth instars were more resistant to the ash (11). Grasshopper control, by low-volume aerial application of insecticide, is normally provided on rangeland by the Department of Agriculture's Animal and Plant Health Inspection Service (APHIS) in cooperation with the states and ranchers. In Grant, Douglas, and western Lincoln counties in Washington, grasshopper populations (mainly second instars) were estimated at 10 to 12 per square meter in May before the ashfall and about 120,000 ha of rangeland were to be sprayed, but the eradication of grasshoppers by the ash and subsequent cool wet conditions was so effective that plans for spraying were abandoned (12). About 130,000 ha were sprayed in this area in 1979, and 150,000 ha were sprayed in eastern Oregon in 1980, where no ashfall occurred (12).

Other crop pests, such as aphids and leafrollers, were in less vulnerable stages in their life cycles or were protected by plant leaves when the ashfall was heaviest, and they escaped serious damage (13). Grain beetles were relatively unaffected by the ash (9) and presumably are adapted to high-dust environments.

Unfortunately, the greatest damage to insects occurred with beneficial species such as honey and pollinator bees (Fig. 2F), predatory and parasitic wasps, and yellowjackets (Hymenoptera). These insects are highly mobile and many have a dense covering of body hairs which traps the dust. The field force of honey bees in the ashfall area of eastern Washington was annihilated on 18 and 19 May (14). Klostermeyer (13) observed that a population of orchard mason bees foraging on 18 May returned to the nest when the sky became darkened by the ash cloud, and were not yet contaminated on the morning of 19 May; but they left the nest on the morning of 19 May since light and temperature were suitable, and they never returned. Johansen (14) estimated that of 15,000 colonies of honey bees in the irrigated Columbia Basin, approximately 12,000 were destroyed or severely damaged. Another 5,000 colonies that would normally have been moved into the Columbia Basin in the spring and summer of 1980 were kept in cleaner areas. The Columbia Basin is a major producer of alfalfa seed and seed production depends on pollinating bees, especially the alfalfa leafcutting bee (*Megachile rotundata*). Since alfalfa pollination had not yet begun on 18 May, some loss of seed production is expected.

Losses of honey and pollinator bees following the 18 May event were estimated at about $1 million. On the other hand, pollination of fruit trees was already completed and many colonies had been removed from the orchards near Yakima and Wenatchee before the major eruption. No shortfall is expected in production of honey in eastern Washington in 1980, since the cool moist spring produced above-normal forage in the clean areas where colonies were concentrated. The populations of bees recovered somewhat in the ashfall area during June and early July.

Preliminary results suggest that the ash is nontoxic to alveolar macrophages (an important part of the natural cleaning mechanism of the lungs); thus it is not predicted to be highly fibrogenic when inhaled by animals (6). This evidence supports the mineralogical data (4, 6) that silica in the ash is not of the type that causes silicosis (6).

An important continuing problem caused by the abrasiveness of the ash is damage to farm machinery. Some estimates suggest that wear to gears, bearings, cutting sickles, and other moving parts of equipment during the growing season of 1980 will equal the wear expected in 3 or 4 years before the ashfall. The problem may not be serious for hydraulic systems that are tightly sealed or for engines equipped with air filters, some of which remove 99.9 percent of potentially damaging (20 μm or larger) particles (15). The moving parts of an engine are separated by an oil film 25 μm thick, so that particles 20 μm and smaller are not expected to be damaging, but the engine must be serviced more frequently than normal. The problem may prove more serious for water pumps in irrigation areas (where ash is suspended in the water) and equipment such as that required for haymaking and grain harvesting.

The ash on wheat seeds decreases the volumetric weight (test weight) of the seeds by a slight but significant amount (16). Apparently the ash acts as an abrasive, preventing seeds from sliding past one another. The bulk density (weight in pounds per bushel or kilograms per quintoliter) is one determinant of price in the marketplace. Wheat from the 1979 crop,

which weighed 58.7 pounds per bushel with no ash, weighed 57.5 pounds per bushel with only 0.025 percent ash by weight, an amount not visible to the unaided eye (*16*). It may be possible to reduce the amount of ash contamination on seed by careful harvesting. The eruption of 12 June occurred when wheat in the Willamette Valley of Oregon was 6 percent headed and that of 22 July occurred when virtually all wheat in eastern Washington was headed but less than 1 percent was harvested. Ash collected within and among the spikes will cause some contamination of the harvested grain. The price to growers drops $0.01 per bushel for each 1-pound reduction in test weight below 60 pounds for soft white wheat, and $0.02 per bushel for each 1-pound reduction in test weight below 58 pounds for club wheat. Since 80 percent or more of the ash is readily removed by the cleaning procedures already used at the flour mills, the loss will be mainly to the farmer. Baking tests have produced no evidence that the ash in flour affects the safety or quality of the flour (*16*).

Effects on Plant Surfaces and Livestock

The ash on plant foliage (Fig. 2, D and G) had at least five kinds of effects: (i) some plants with weak supporting stem tissues lodged under the sheer weight of ash; (ii) photosynthesis was slowed and even prevented by ash acting as a light barrier and clogging leaf stomata (*17*); (iii) where the ash was wet (for instance, in western Washington on 25 May), some salt damage developed on leaves and fruits; (iv) leaves with ash were slightly cooler (about 1°C) than leaves without ash because of their greater reflectance of incoming radiation (*18*); and (v) leaf water potentials became more negative (up to 4 bars lower) for a few days (*18*), possibly because of damaged cuticles. The ash has seemed to cling tenaciously to leaf surfaces and has been difficult to remove by washing. Plant species with hairy (pubescent) leaf surfaces will not be entirely free of ash until the new leaves develop next year, whereas plants with smooth (glabrous) leaves have tended to shed the ash more readily. Premature leaf drop has occurred on some shade trees.

Loss to winter wheat from lodging has been estimated at less than 5 percent. Most of the ash was shed from the wheat foliage and settled in a uniform layer around the bases of the stems (Fig. 2B), where it will remain undisturbed until the field can be cultivated. A record 150-million-bushel wheat crop is expected in Washington in 1980, mostly because of the above-normal rainfall in June. The ash layer may even have increased yields in some wheat fields by slowing evaporative loss of water from the soil surface.

The lodging problem has been especially important in alfalfa hay in the irrigated Columbia Basin (for instance, Grant County). Alfalfa is a prized forage crop, in part because the plants have abundant delicate leaves and stems that are highly palatable to livestock. The same attributes made the crop vulnerable to lodging under the weight of the ash. The crop in Grant County was ready for the first cutting, and some was mowed but not yet baled. An estimated $35 million was lost in alfalfa hay production, about two-thirds of it in Grant

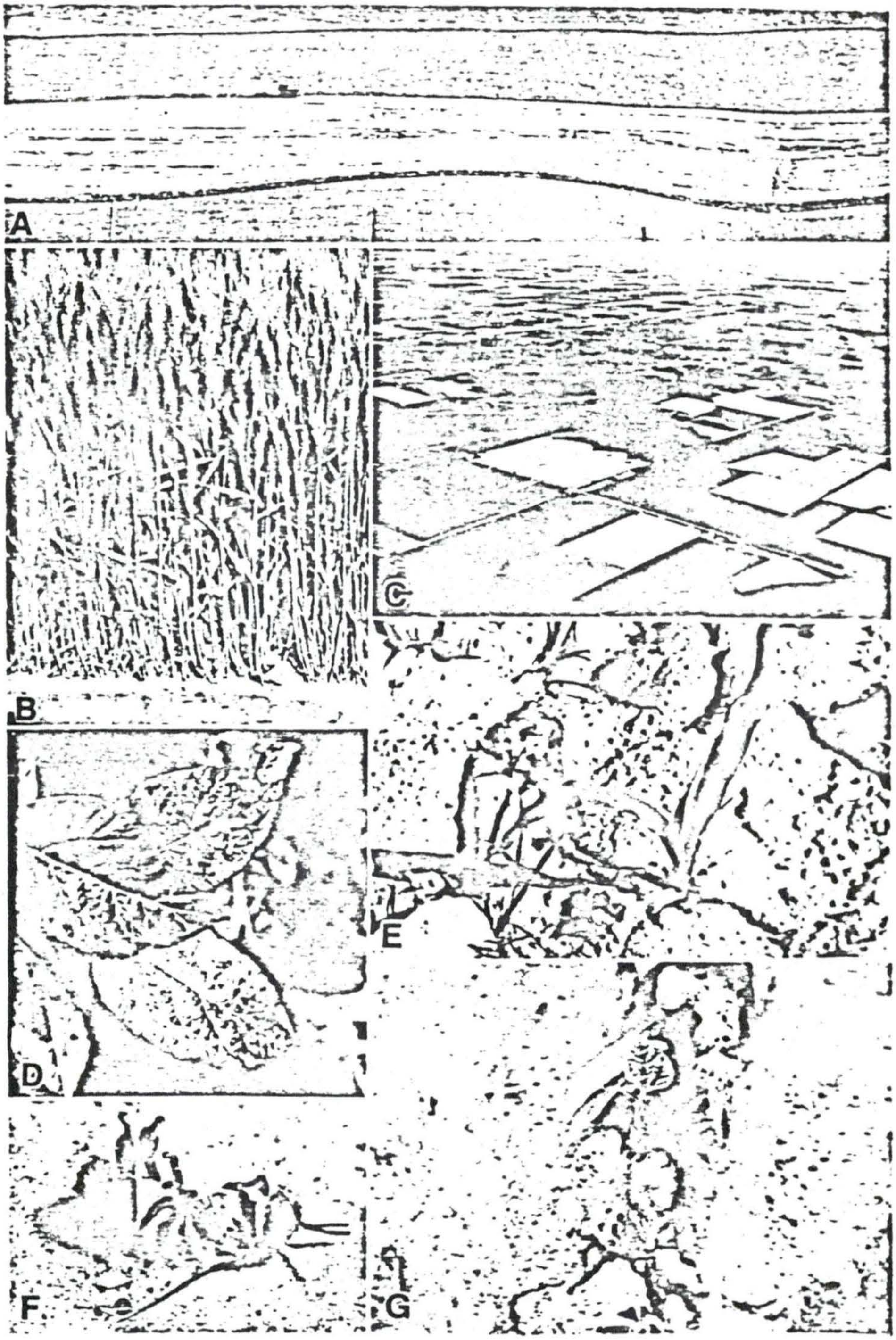


Fig. 2. Examples of effects of ashfall on crops, soils, and insects in eastern Washington after the eruption of Mount St. Helens on 18 May. (A) Incorporating ash with tillage near Dayton; (B) ash deposited on soil surface around stems of wheat plants near Lind, revealed by excavation; (C) aerial view the week after ashfall near Othello, where fallow or newly planted fields were white but fields with adequate plant canopy hid the ash from view; (D) potato leaves with adhering ash 1 week after ashfall (photo by W. B. Dean); (E) corn seedling in 1.5 cm of impacted ash near Moses Lake (photo by R. L. Wample); (F) honey bee killed by ash (photo by R. D. Akre); and (G) ash-laden bean seedlings near Othello (photo by W. B. Dean).

County. Some 5,000 ha (out of 35,000 ha) in Grant County had been plowed or disked under by 1 July.

Alfalfa harvested as hay after the ashfall, either standing in the field or in the windrow, contained up to 60 percent ash (dry weight basis); typical contents ranged from 5 to 15 percent. Since much of the alfalfa hay in eastern Washington is trucked to dairy farms in western Washington, the cost of transportation was increased. A discount rate based on ash content was developed (*19*) for sale of the hay.

Although it might affect the rate of weight gain in animals, the ash is apparently nontoxic in livestock feed. Concentrations of heavy metals such as As, Cd, Co, Cu, and Mo are below levels toxic to livestock, even if the ration contained 10 percent ash by weight (*19*). Day-old chicks, which are highly sensitive to diet, showed a 6 percent reduction in growth rate for each 10 percent increase in the ash content of the diet, compared to a 4 percent reduction for the same amount of sand in the diet. Mortality was unaffected by up to 30 percent ash in the diet (*20*). Two lactating cows produced milk at the expected level over a 5-week period during which the ash content of their ration was increased at weekly intervals to a maximum of 6.3 percent in the fifth week. Dairy calves fed a ration containing 10 percent ash for up to 4 weeks grew normally and, when slaughtered, showed no accumulation of ash in the gastrointestinal tract and no abnormal internal symptoms (*19*). Milk production has not been reduced in the affected area, according to production records of the Dairy Herd Improvement Association and delivery reports in the three major markets under federal milk marketing orders (*21*).

Apple leaves, being pubescent, trapped considerable ash, so that photosynthesis virtually ceased. A coating of ash 1 mm thick, which was not uncommon on leaves of apple trees in the heavier ashfall area for up to 1 week after the 18 May event, reduced photosynthesis by 90 percent (*17*). In an orchard at Pullman, and where ash deposits were lighter, photosynthesis in apple leaves was temporarily reduced by 25 to 33 percent, compared to rates measured immediately before the eruption (*17*). This reduction occurred at a time when the rate of photosynthesis would normally be increasing or at least stable. In addition, the CO_2 compensation point was 25 to 50 percent higher in leaves on ash-coated trees at Pullman than in leaves on ash-free trees (*17*)—an indication that photorespiration was increased.

The apple trees in some orchards in the Yakima Valley, normally among the earliest to be harvested, exhibited some premature fruit drop, possibly because of the reduced rate of photosynthesis that followed ashfall. Orchards where ash was removed immediately by wind devices or sprinkler irrigation had less trouble with fruit drop. In an area near Royal Slope (Grant County), 500 ha of the Red Delicious cultivar of apples and 250 ha of the Golden Delicious cultivar received 2 to 3 cm of ash on 18 May; fruit drop caused loss of about 75 percent of the Red Delicious and about 5 to 10 percent of the Golden Delicious. Total loss of apple production in the ashfall area is estimated as less than 10 percent, or about $15 million. On balance, the few apple fruits that remain on trees after heavy fruit drop are expected to be of a better size and grade and help offset the loss from fruit drop. The total apple crop is expected to be 5 to 10 percent above the 1979 crop. The Wenatchee and Okanogan apple-producing areas escaped damage from the 18 May event.

Fruit of peaches and apricots, which are also highly pubescent, could not be readily cleaned of ash, and consequently a significant percentage of the crop could not be sold after the 18 May event. In Clark County, about 75 percent of the raspberries became unacceptable for processing because ash from the 12 June ashfall could not be removed by washing. Also after the 12 June ashfall, about 40 percent of the strawberry crop in northwestern Oregon and southwestern Washington was rotted in the field; the ash-covered leaves compressed the fruit to the soil surface, where conditions for infection and decay were ideal (*22*). In western Washington the wet ashfall on 25 May occurred when blueberries were nearing maturity; 20 to 40 percent of the fruit developed damage (apparently from salts in the ash) and could not be sold.

Several plant diseases favored by cool moist conditions were epidemic in eastern Washington crops in 1980, mostly because of the cool moist season, but in some cases possibly because of ash deposits. The most significant disease in peas in 1980 was white mold caused by the fungus *Sclerotinia sclerotiorum*. The moist ash layer on soil apparently provided ideal conditions for germination, and the resulting spore-bearing apothecia on stipes had no problem emerging through the ash (1 to 2 cm deep) in the eastern Washington pea-growing area. The combination of abundant spores, susceptible crop, and cool moist weather needed for disease development caused significant loss of peas in some fields by late July and reduced yields overall by an estimated 10 percent (*23*). Also on peas, *Phoma medicaginis* caused a black decay of the cortex on stem tissue from the soil-ash interface and up into the ash zone. The distinct zone of attack near and in the ash zone indicates that moisture and temperature were most suitable for the pathogen in this niche, that some component in the ash stimulated the pathogen, or that the stem was predisposed to the infection. In spite of the losses from these diseases, a normal pea crop is expected in Washington and Idaho in 1980 and yields in individual fields are among the highest ever for the area because of the ideal moisture and temperature for peas in eastern Washington in 1980 (*23*).

On wheat, an important basal stem rot (foot rot) caused by *Cercosporella herpotrichoides* may have been favored in areas that are commonly too dry (annual rainfall 25 to 30 cm) for this disease (*24*). Cultural practices that cause soil to collect around stem bases of wheat are known (*25*) to favor this disease because of the "moist chamber" effect. Many growers in areas with higher rainfall where foot rot was expected had sprayed their fields with a fungicide in March and April, and consequently were spared what might have been a serious epidemic. The actual contributions of the ash layer to this disease are difficult to separate from the contributions of the cool wet spring.

Ash cover among the grasses and shrubs in the steppe vegetation zones of Washington State (Fig. 1B) may eventually create new safe sites for plant invasion and colonization, particularly by alien weeds such as *Bromus tectorum*. Studies of the Katmai volcanic district in Alaska (*26*), Paricutin in Mexico (*27*), and the Kilauea volcano in Hawaii (*28*) suggest that the process of vegetation of the newly created safe sites may be similar to that of plant invasion and colonization of sand dunes. One expected similarity is the early establishment of seedlings in polygonal cracks or other disturbances such as animal tracks in the ash layer, as observed by Griggs (*26*) in Alaska.

One alien weed, *Verbascum thapsus*, had more negative leaf water potentials (−3 to −4 bars at midday) on ashed than on nonashed plants on 20 May, but on 14 July leaf water potentials were the same for plants with and without ash (*18*). Stomatal resistance was also the same in mid-July for plants with and without ash (*18*). Thus weedy aliens now seem not to differ from (ash-free) control plants.

Influence on Soil Surface and Some Long-Term Implications

At least 99 percent of the ash settled as a layer on the soil surface within a few days of each ashfall. Bare fields became almost as white as snow (Fig. 2C) after the 18 May eruption. Unlike snow, however, the ash does not melt, dissolve, or percolate into the soil profile; it is moved primarily, if not only, by erosion processes or machines. The effects have been subtle but significant; for instance, the ash-covered surface has a higher albedo and a lower permeability for water than the underlying soil. These effects may continue for years in undisturbed areas such as rangeland and may persist to some extent in cultivated areas even after the ash is fully incorporated with the tillage layer (Fig. 2A).

The greater reflectance of ash-covered surfaces, which is due to the pale gray color of the ash, has resulted in lower peak soil temperatures and less water evaporation. Reflectance of such surfaces has been estimated as 40 to 60 percent. By comparison, fresh snow reflects 80 to 85 percent and ash-free soils in the ashfall area reflect only about 15 to 20 percent of incoming radiation. Peak daytime soil temperatures measured in late May beneath 2 to 3 cm of undisturbed ash were 6° to 10°C lower than those of adjacent sites with ash incorporated.

Warm-temperature crops that were planted in the spring, such as corn (Fig. 2E) and beans (Fig. 2G), were mostly just emerging in middle to late May in the irrigation areas of east-central Washington (for example, Moses Lake). These crops essentially ceased growth until the field was cultivated and the soil temperature could rise. Seed and seedling blight caused by *Pythium* spp. and favored by cool moist soil resulted in a reduced growth rate and even some loss of stand in fields of corn and beans in the Columbia Basin, and possibly also lentils in eastern Washington and northern Idaho. In contrast, potatoes emerged through compacted ash with no trouble and have shown no adverse effects to date.

The fact that the ash has a lower permeability for liquid water than the soil is related in part to its lack of continuous pores for both capillary and saturated flow. The range and distribution of particle sizes of the ash and the angular shape of the particles are such that the fines readily fill in the spaces around the coarser fragments, thus reducing the porosity and flow paths and creating dead-end spaces that do not conduct water. The pore arrangement of the ash would also reduce its permeability to air and water vapor compared to most soils.

The surface ash layer is also expected to retard evaporation of water from the soil and keep the soil wet longer during rainless periods. The ash layer acts as a surface mulch, both reflecting incident shortwave solar radiation (which reduces the energy available for evaporation) and barring liquid water flow and evaporation from the soil to the atmosphere. It appears likely that the ash layer, where left undisturbed, will for a time increase the supply of water for plants. Even after cultivation and mixing, the soils are lighter in color than they were before the ashfall, especially in areas of heavy deposition. Thus the effect of reduced evaporation may be expected to persist for some time on croplands and on disturbed range and woodlands.

A major concern in the ashfall area is the potential effect of ash in reducing infiltration of rain, snowmelt, and irrigation water into the soil. Preliminary estimates from rainfall simulator studies indicate that the low-intensity winter rainfall common in the ashfall area will infiltrate at near-normal rates of 0.5 to 1.5 cm per hour (*29*). However, if rainfall or snowmelt is heavy during the coming winter months, above-normal runoff may occur in undisturbed sites. Regardless of rainfall intensity, the sediment load of runoff is likely to increase because of the high erosivity of the ash.

Some runoff occurred immediately after the 18 May ashfall in irrigated fields where overhead sprinklers were used. This problem was quickly resolved by reducing the water application rate and cultivating the soil to break up the ash layer and establish macroporosity for water percolation. Runoff and erosion also occurred after intensive rains in late May and June in ash-covered nonirrigated fields with little or no plant cover.

What appears the most practical solution for improving infiltration on croplands is to cultivate and incorporate the ash with the tillage layer (Fig. 2A). However, extra cultivation requires extra fuel, and the additional loosening and stirring of the soil increases the hazard of erosion through loss of surface crop residues and destruction of the natural soil structure. There is little agreement at present on how best to incorporate the ash or when to cultivate. Many farmers in eastern Washington and adjacent Idaho have recently begun practicing no-till planting (crop seeding directly into undisturbed soil) to save fuel and reduce soil erosion. This emerging practice for cereal grains and dry edible legumes may be set back 1 year or more as some growers return to conventional tillage to incorporate the ash. In Whitman County, the area planted with no tillage had increased from about 3000 ha in 1976 to about 7000 ha in the fall of 1979, but may be less again in the coming season. Nevertheless, these and other problems associated with slower infiltration on cropland soils are likely to be of short duration.

Another major concern for agriculture and the Pacific Northwest in general is that increased wintertime runoff from the vast ash-covered watersheds (normally undisturbed range and pasture lands, woodlands, and forests) will affect the supply or continuity of supply of water to rivers and irrigation reservoirs. Restricted infiltration in areas with significant ash deposition will disrupt the natural hydrology of the region. Water from rain and snowmelt will be shed more rapidly, which will increase the hazards of flooding and erosion. A more gradual release of runoff, such as normally occurs from these areas, is needed to maintain adequate reservoir levels through the critical irrigation period. High runoff also produces sediment-laden water, which is not only of poor quality but also hastens sedimentation behind large reservoirs. At this time, it appears that little can be done through management to modify the potential effects of ash on the noncropland watersheds, and these could persist for years.

Wind erosion may also be more severe for the next few years, or until the ash has stabilized. As reported by Griggs (*26*) for the Katmai volcanic district in Alaska, the dry ash behaves physically like unstabilized sand and forms embryonic dunes or foredunes around plants and other obstructions. Griggs reported that the silt-sized ash forms a nonerodible layer when slightly wetted. However, the ash in eastern Washington is believed to be highly erosive when dry.

Since ash contains no organic matter, its incorporation into the tillage layer will dilute and hence lower the organic matter content of the soil. The effect could be significant in areas where deposits were heaviest (Fig. 1) and where the organic matter content was already low (~ 1 percent) before ashfall. For example, an ashfall of 225 metric tons per hectare would reduce the organic matter content of the tillage layer by about 10 percent. Certain herbicides applied to soil for weed control will damage crops where organic matter is low; the margin of safety for these herbicides may need reevaluation in areas with heavy ashfall.

Some of the elements in the ash are essential plant nutrients, which has prompted speculation that some im-

provement in soil fertility might occur. Unfortunately, the elements are mostly unavailable. Analysis of the available (and hence biologically significant) nutrients showed the following concentrations (in parts per million): P, 1 to 5; K, 120 to 180; Cu, 3 to 5; Fe, 15 to 40; Zn, 0.5 to 1; Mn, 10 to 20; and S as sulfate, 250 to 450 (*8*). With the possible exception of sulfur, the amount of each element available is insufficient to change current fertilization practices. Moreover, the prospect for release of these unavailable nutrients by weathering and other processes seems poor. Other ash layers in the region deposited thousands of years earlier have changed very little (*30*). In short, as a soil material the ash may prove biologically quite inert.

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32. Charts A and C in Fig. 1 were redrawn from data provided by M. M. Folsom and R. R. Quinn. Chart B was redrawn from R. Daubenmire, *Wash. Agric. Exp. Stn. Tech. Bull. 62* (1970).

33. We recognize with gratitude the information provided so generously by the research and extension faculty and students of Washington State University, including F. M. Entenmann, Cooperative Extension Service; E. Klostermeyer and other faculty, Department of Entomology; R. A. Kennedy, Department of Horticulture; R. Preston, Department of Animal Science; G. L. Rubenthaler, Wheat Quality Laboratory, U.S. Department of Agriculture; and R. K. Sorem, Department of Geology. We also thank M. M. Folsom and R. R. Quinn, Eastern Washington University, Cheney; C. Knowles, Idaho Bureau of Mines and Geology, Moscow; and W. Moen, Division of Geology and Earth Resources, Department of Natural Resources, Olympia, Wash., for providing information on the nature and amounts of ash.

The Hawaii to Tahiti Shuttle Experiment

Klaus Wyrtki, Eric Firing, David Halpern, Robert Knox
G. J. McNally, W. C. Patzert, E. D. Stroup, B. A. Taft, R. Williams

The Hawaii to Tahiti Shuttle Experiment has three distinct roots. The first is the work of Bjerknes (*1*), who analyzed ocean-atmosphere interactions associated with the 1957 El Niño event and concluded that large-scale events in the equatorial Pacific Ocean are caused by feedback between ocean and atmosphere and have global consequences. The second root—and the original idea for a shuttle—is Montgomery's 1969 study of the meteorological observations that were made by passenger ships between Hawaii and Tahiti (*2*). He concluded that such simple observations of parameters of the air-sea boundary made by these ships are adequate to detect and describe the low-frequency changes of the ocean-atmosphere system in the central Pacific. He recommended that a transequatorial shuttle program on ships of opportunity be implemented. The third root is an investigation by Wyrtki (*3*) of the relations between flow in the countercurrent, sea level difference across the current, and temperature in the eastern equatorial Pacific, where the countercurrent terminates. He showed that the flow is subject to large interannual variations and that strong flow is concurrent with warming in the eastern equatorial Pacific and El Niño events off Peru.

In the early 1970's the North Pacific experiment (NORPAX) was begun as part of the International Decade of Ocean Exploration. It was based on the ideas of Namias (*4*) and Bjerknes (*1*) concerning the large-scale interactions of ocean and atmosphere and the use of these relations and teleconnections in long-range forecasting. One of the most pronounced climatological events in the Pacific Ocean is, of course, El Niño, and a new theory about its mechanism was developed by Wyrtki (*5*), who analyzed the trade wind field and sea level records. It was shown that, after a period of sustained, strong southeast trade winds, much warm water is accumulated in the western Pacific, and that as soon as the trade winds relax, the water surges back along the equator. This theory was tested and confirmed by analytical and numerical models (*6*) which show that the adjustment of the thermocline is accomplished primarily by an internal Kelvin wave. The changes in ocean structure in the western and eastern Pacific associated with El Niño could be confirmed by

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Mount Saint Helens Blows the Season For Many Washington Beekeepers

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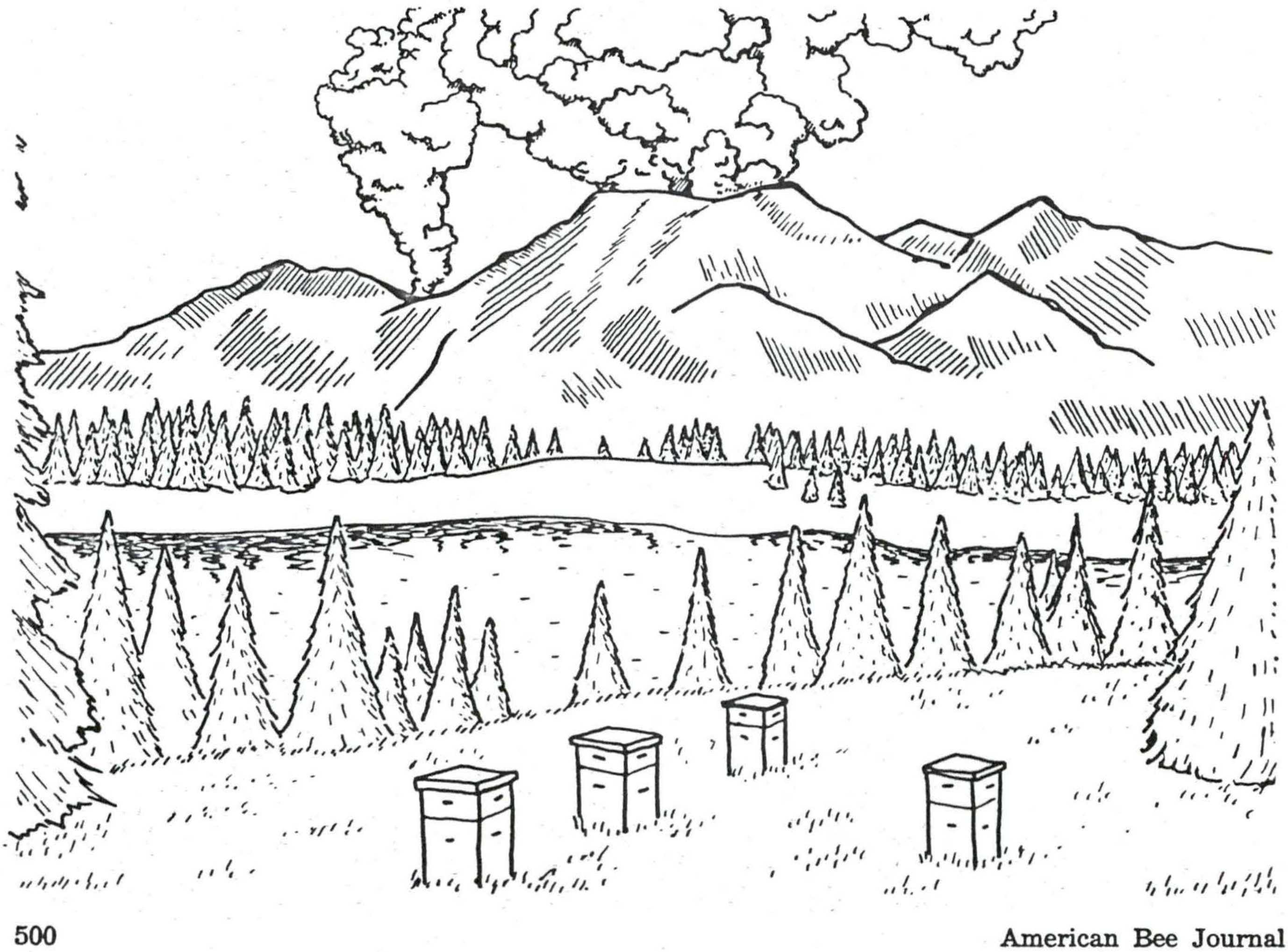
ABOUT 8:30 a.m. on Sunday, May 18, 1980, the long-dormant volcano, Mt. St. Helens erupted with explosions heard at least 200 miles away. At Pullman, I was using a Weed-eater when it began to get dark about noon. I worked around to the edge of the carport to be out of the "expected rain." Instead, it became black as pitch by 2 p.m., with a red glow on the horizon to the south and a light stripe to the east. From that time until 2 a.m. the following morning, predominantly gray-white ash fell, reflecting in the street lights and car headlights. About 6:30 p.m., the sky lightened somewhat before the invisible sun set.

Most persons could not have imagined in advance what a tremendous ash fallout was going to occur. Spokane, with $\frac{1}{4}$-$\frac{1}{2}$ inches was calculated to have about 8 tons/acre. About $\frac{3}{4}$ of an inch of coarser, sandier stuff fell on Yakima, not so much of the microfine material we are still cleaning up. Among the heaviest hit areas, 2 to $3\frac{1}{2}$ inches fell at Vantage, Matawa, Moses Lake, Royal Slope, Ritzville and Rosalia.

We quickly found any insects which got into the ash were dying within 3-6 hours. At first we assumed the ash was scurfing the surface wax layer and allowing the insects to desiccate. However, it also appears likely that their tracheal (breathing) tubes were being plugged by the smaller particles, 1 micron or less in diameter. Yellowjackets and bumble bees were being severely reduced because wintered queens were being killed before their annual nests were established.

We thought that honey bees might survive reasonably well since there had been warm weather preceding the eruption and good stores and quantities of brood and hive bees were present. However, the field force was completely annihilated. As long as no rains or other cleansing effect occurred, the bees continued to die each day. Even



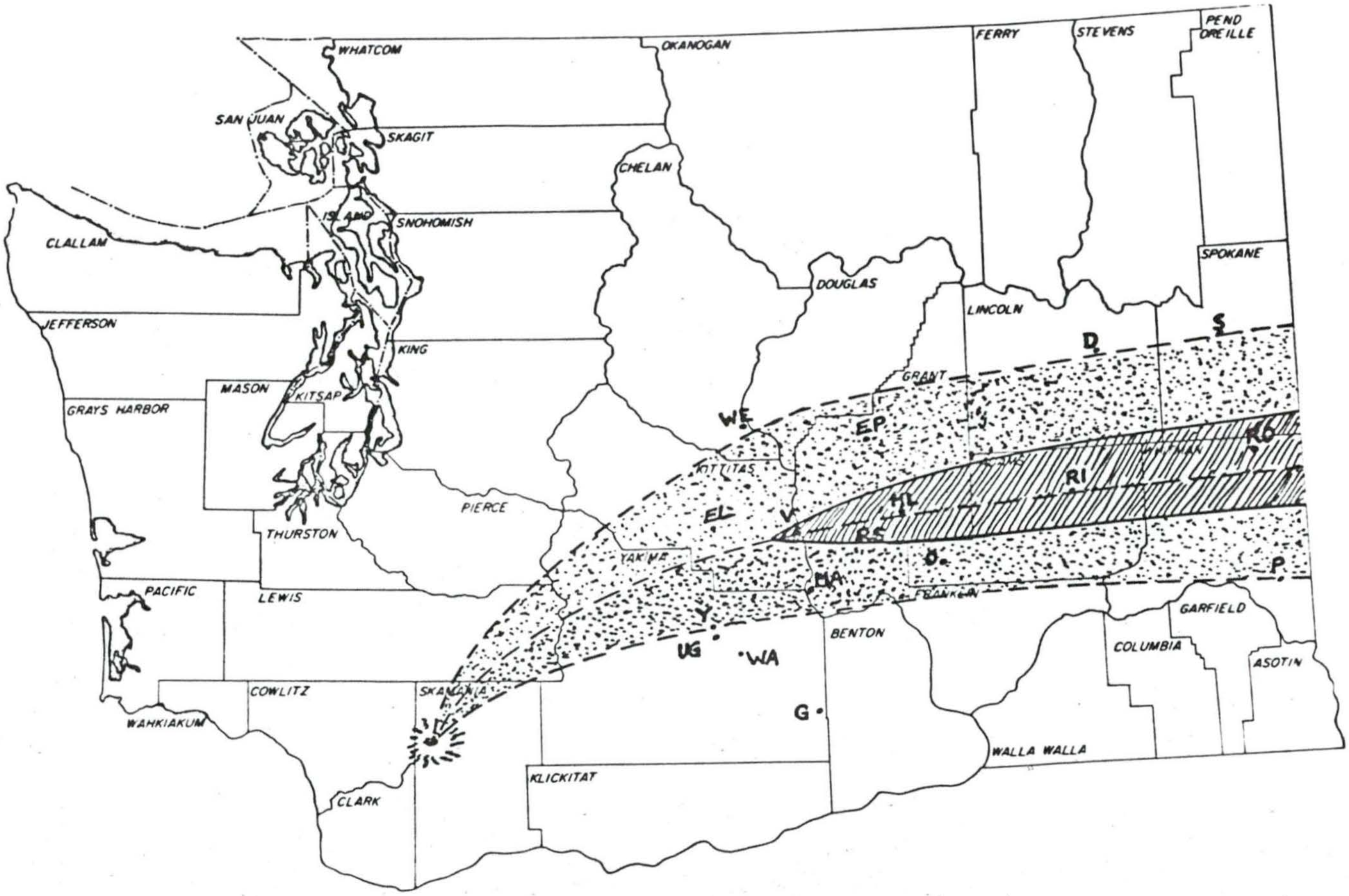


Fig. 1. Map of Washington showing major volcanic ash fallout area. Dashed lines coincide with records of about ½ inch, darkened center is area with 2-4 inches. Symbols are: WE, Wenatchee; D, Davenport; S, Spokane; EL, Ellensburg; EP, Ephrata; V, Vantage; ML, Moses Lake; RS, Royal Slope; RI, Ritzville; RO, Rosalia; Y, Yakima; UG, Union Gap; WA, Wapato; G, Grandview; MA, Matawa; O, Othello; P, Pullman.

following rains, as soon as the ash dries out it begins to blow around again and the whole area can become completely engulfed in the dust clouds. When the colony becomes too weak to clean itself (housekeeping bees are also lost as they get into the dust on the landing board), uncapped brood begins to die from dust contamination.

I talked to Sidney Hiatt, Ephrata, on Thursday, May 22. He felt he had to get several thousand colonies out of the Moses Lake and Royal Slope areas and up around Omak where little or no ash fell. He had to get outside air cleaner devices installed on his trucks in order to do the job. Eugene Blackwell, Ellensburg, told me they had been syruping and medicating their bees in the Vantage and Matawa areas, trying to keep them going. Robert Longanecker, president of the Washington State Beekeepers Association, appointed a committee to determine losses to the fallout in eastern Washington. Ronald Knopp, Moses Lake, and Richard Bates, Ephrata, are checking the

*All photographs by Roger D. Akre, Department of Entomology, Washington State University.

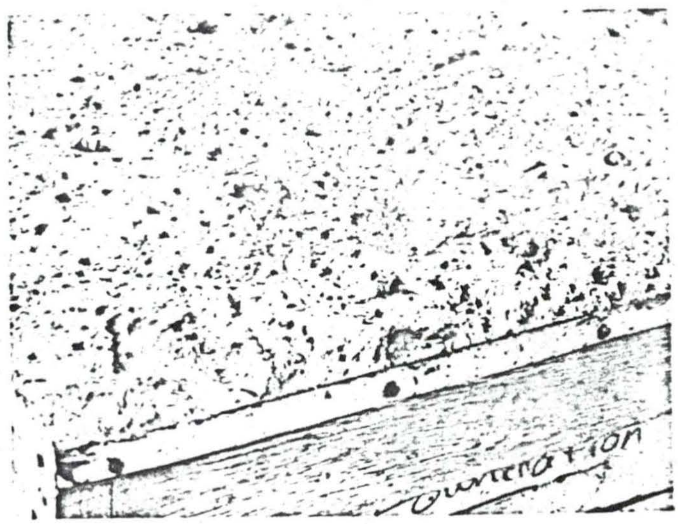


Fig. 2. Dead honey bees in volcanic dust on top of hive, Pullman, WA, May 21, 1980.*

Columbia Basin area; Lyle Hibbard, Grandview, and Elwood Sires, Union Gap, are checking central Washington. Much of the data I will cite was obtained through them.

Lack of summer pasture has been one of the main underlying causes of severe bee poisoning problems in Washington for many years. Now, the volcanic ash has severely restricted what little forage was previously available. Not only will many beekeepers be forced to leave the areas of greatest impact, but also persons in unaffected areas will end up sharing meager nectar flows with those who move.

Of the 15,000 colonies in the worst-hit areas, it seems likely at least 12,000 will be destroyed. There are about 5,000 additional colonies which would

normally be placed in the Columbia Basin. Instead, these will remain in cleaner areas and increase the bee pasture problem.

It is difficult to estimate potential losses at this time. Sidney Hiatt is moving bees out of the heaviest fallout area and is changing air and gas line filters at least every trip. Rains finally started to fall in the Columbia Basin and Yakima Valley on May 26. But, no one knows what effects the continued presence of the dust will have on bees during the summer. The beekeepers have estimated a $2 million loss covering all sources of income: severe reduction in honey production; loss of normal colony increase; loss of summer pollination fees; loss of contaminated beeswax which cannot be salvaged; and losses due to normal operations which cannot be accomplished or to special costs of equipment and labor expended to cope with the situation. ●

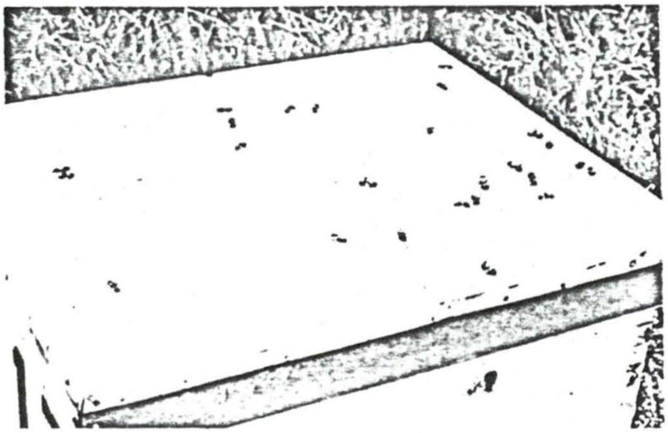


Fig. 3. Dead honey bees in volcanic dust on top of hive after rain, Pullman, WA, May 22, 1980.

Fig. 4. Closeup of dead honey bee in volcanic dust on top of hive following rain, Pullman, WA, May 22, 1980.

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